USE OF A PCM ACCUMULATOR IN TEMPERATURE-CONTROLLED TRANSPORTATION OF FOODSTUFFS

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ABSTRACT

Temperature-controlled transportation of foodstuffs is usually carried out by lorries and trucks having a diesel engine-driven refrigeration unit. It would be desirable to reduce the exhaust gas and noise emissions of the diesel-driven coolers. The objective of the project was to study whether it would be possible to temporarily switch off the diesel-driven refrigeration unit and keep the foodstuffs at the right temperature with the help of a PCM accumulator. A test module was built and the function of it was tested in a test box equipped with a refrigeration unit. Based on the test results, the performance of a full-size lorry was estimated using a numerical simulation model. According to the simulations, a PCM cold accumulator is able to keep the inside temperature of an empty lorry within the desired limits for about 5 hours when the outdoor temperature is +30 ^{o}C.

1. BACKGROUND

The transportation of foodstuffs within certain temperatures is regulated by international standards /1/. The cold transportations can roughly be divided into cold and frozen transportations. Frozen transportations should be done under -18 °C and cold transportations between 0 – 15 °C, depending on the transported foodstuffs. For example, the temperature during transportation of ready-made food should be from 0 to + 6 °C.

Normally, the temperature control of the transportation equipment is realized with the help of diesel-driven refrigerators, which cause exhaust gas and noise emissions. These should be avoided, especially in densely populated areas. The objective of the project was to study whether it could be possible to temporarily switch off the diesel-driven refrigerator and keep the foodstuffs at the right temperature with the help of a PCM accumulator.

A delivery lorry with one refrigerator was chosen as the target application for this study. In practice, the same lorries and trucks are used for cold transportations at different temperatures. In multi-temperature transportations, the different temperature spaces are separated by walls or curtains and cooled with separate evaporators. Refrigerated transport is needed from producers to distribution centres as well as from distribution centres to stores and shops. The PCM accumulator could be charged during longer driving distances and discharged in densely populated areas.

A building energy dynamics software called VTT Talo /2/ was used for the numerical simulations. This enables describing and simulating the thermal behaviour of a cargo space, it's construction, and heating and ventilation system. Following the recent update to the software, /3/ the wall structures can also include PCM layers. PCM storages can be simulated as well.

2. PCM SELECTION

The melting point of the PCM was chosen for transportation of ready-made food. The availability and performance of commercial PCM materials for the selected application and temperature range was evaluated. RT2 paraffin by Rubitherm GmbH was chosen as the phase change material. RT2 paraffin is stable, its latent heat is moderate – about 200 J/g – and the phase change occurs within a narrow temperature range. The subcooling of RT2 is only a few degrees. The DSC curve of RT2 as measured by the TA 2920 instrument is presented in Figure 1.

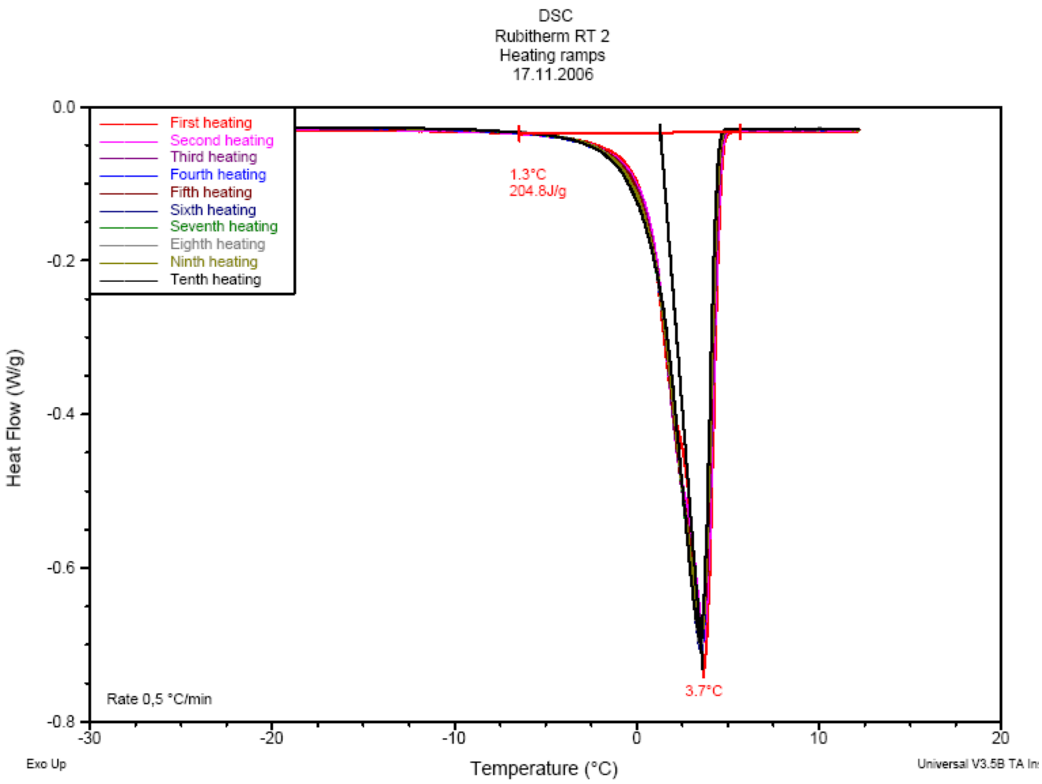

Figure 1. Ten DSC heating cycles of the Rubitherm RT2.

3. PROTOTYPE DEVELOPMENT

A test module of the PCM cold accumulator was built at VTT. The area of the test module was 2 m^2 and the thickness 10 mm. The prototype was made of an aluminium honeycomb. In a previous study the thermal conductivity of the aluminium honeycomb filled with paraffin was measured to be 2.1 W/Km /3/. The thermal conductivity of pure paraffin is about 0.25 W/Km. One mm-thick aluminium sheets were bonded onto both surfaces of the honeycomb with an epoxy glue. The honeycomb was filled with 10.6 kg of the RT2 paraffin by vacuum injection, as shown in Figure 2, and the surface sheets were painted black to improve heat transfer by radiation.

Figure 2. Vacuum filling of the PCM prototype. The PCM accumulator is between wooden plates during the filling.

4. MEASUREMENTS IN THE TEST CELL AND MODEL VERIFICATION

Initial calculations performed by the VTT Talo numerical simulation program had indicated that a thin PCM sheet or plate in the ceiling of the cargo space would show good performance. Therefore, the prototype module was assembled on the ceiling of a small test cell measuring 2x2.5x0.9 m^3 equipped with a refrigerator by Lumikko Ltd. and tested there. The objectives of the measurements were to verify the numerical simulation model in this specific application and to see if the panel can be charged simply by blowing cold air from the evaporation unit onto the lower PCM panel surface. The setup is shown in Figures 3 and 4.

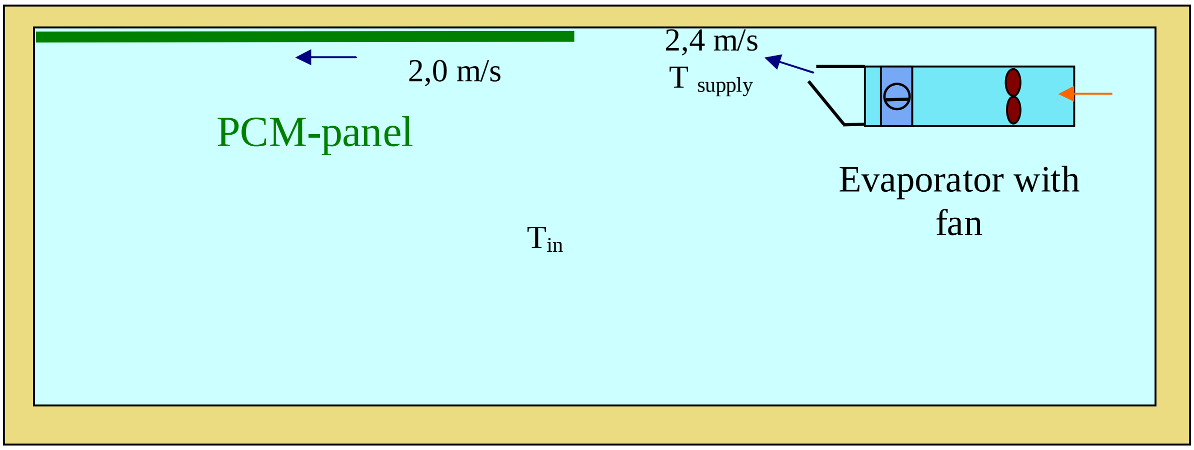

Figure 3. Location of the PCM prototype module and the refrigerator unit in the test cell.

Figure 4. The PCM prototype module was assembled on the ceiling of the test box. The prototype is on the right and the refrigeration unit is on the left.

The PCM was crystallized with the cold air from the refrigerator during the charging period. The refrigerator was stopped after the PCM was fully crystallized but the fan was still blowing in order to increase the convective heat transfer from the air to the PCM module during discharge. The temperatures in the test box and on the PCM module surface were continuously monitored.

The measured temperatures in the test cell during the discharge period are shown in Figure 5 along with the simulated temperatures. The agreement is reasonable and it seems that the discharge period is fairly easy to predict with the computational model. A case with an empty test cell without PCM is also included in Figure 5 to show that the heat capacity and the heat losses of the test cell have been modelled correctly.

The temperature of the test box was under the required + 6 °C for nine hours. It was estimated that 3 hours could be attributed to sensible heat and 6 hours to the latent heat of the PCM.

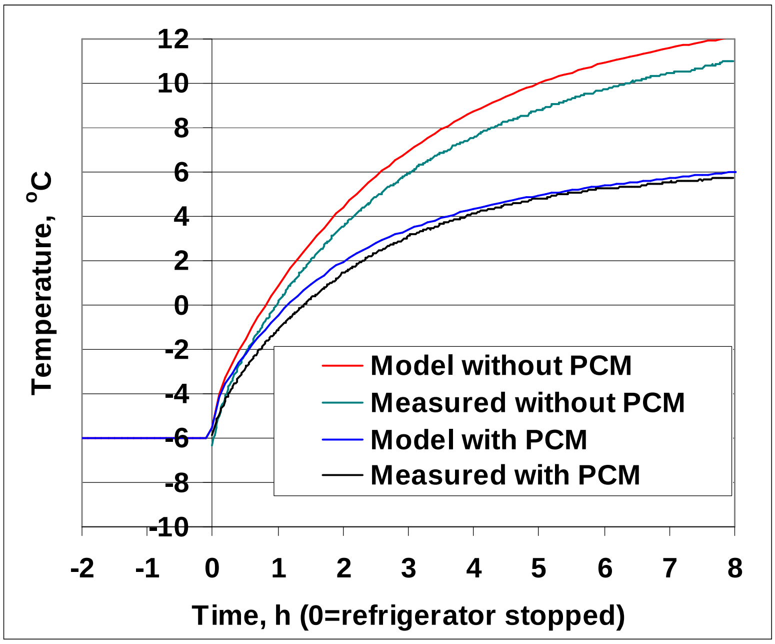

Figure 5. Measured and simulated temperatures in the test cell during the PCM discharge period.

The performance during the charge period is less satisfactory. To work during the discharge period as well, the PCM in the accumulator must be crystallized completely, as seen in Figure 5. It turned out that the temperature of the supply air from the refrigerator for loading the PCM module in a reasonable time had to be about -10 °C. This temperature is far too low for the foodstuffs being transported, even if the air temperature in the cargo space is a few degrees higher than the air supply temperature. The crystallization of the test module was also tested with 0 ^{o}C air, but the crystallization took more than 8 hours, which is not acceptable. It remains a challenge to find other methods to crystallize the PCM without affecting the foodstuffs.

5. SIMULATED PERFORMANCE OF A FULL-SIZE LORRY

Based on the test results, the performance of a full-size empty lorry was estimated using the VTT Talo model. The empty lorry represents a worst case scenario as the precooled foodstuffs being transported increases the thermal capacity of the system. According to the simulations, a 5 mm-thick PCM cold accumulator in the ceiling of the lorry is able to keep the inside temperature within the desired limits for about 5 hours when the outdoor temperature is +30 ^{o}C and there is no air leakage to the cargo space. Figure 6 shows that the effect of air leakage through the loading doors can be remarkable.

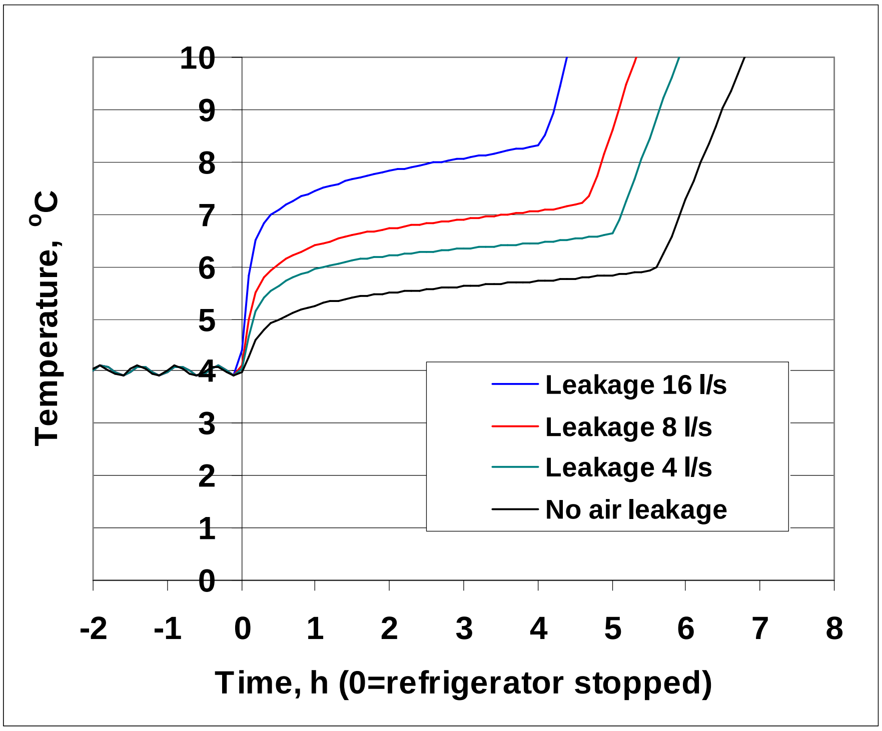

Figure 6. Computed temperature inside the cargo space with different air leakage flow rates. The whole ceiling is covered with PCM panels. Natural convective heat transfer to the panels is slightly enhanced with a fan.

Effective heat transfer from the cargo space to the PCM panels is essential in keeping the air temperature within the desired limits. It seems that natural convection heat transfer is not enough and a slight enhancement, for example with a fan, is needed to double the convective heat transfer coefficient. Radiation heat transfer is also important, covering about one-half of the heat flow to the panels.

6. CONCLUSIONS

The PCM cold accumulator could keep the temperature of the test box below + 6 °C for nine hours. According to the simulations, a 5 mm-thick PCM cold accumulator in the ceiling of the temperature-regulated cargo space of a food transportation lorry is able to keep the inside temperature within the desired limits of 0 to + 6 °C for about 5 hours when the outdoor temperature is +30 °C. To work as well as this, the PCM in the accumulator has to be crystallized completely. Complete crystallization of the PCM within a moderate time needs air that is approximately -10 °C. Such cold air cannot be blown to the lower surface of the PCM accumulator during driving because the foodstuffs will freeze. The other problem is that the same distribution lorries are used at different temperatures for different foodstuffs and even multi-temperature transportations are commonly used. A permanently installed PCM accumulator tailored for one temperature in the ceiling of the lorry doesn't work in these cases.

The performance of the PCM accumulator during discharge is promising but other means of charging, e.g. precharging outside the lorry or blowing the cold air between the PCM module and the ceiling, should be developed.

ACKNOWLEDGEMENTS

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